LEVEL II

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APPLICATION OF PROCESS MODELING TO SHELL DRAWING OPERATIONS

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The manufacture of artillery shells involves a number of metalforming, machining, and heat treatment operations. Cold or hot drawing of shells, where the wall thickness of the shell is reduced while keeping the inner diameter essentially unchanged, represents an important step in the forming operations. From the point of view of deformation mechanics, the analysis of metal flow and stress in shell drawing is very complex. The effect of friction at the tool-material interface, the heat generation and heat transfer during deformation, and the effect of strain, strain rate and temperature on the flow properties of material are difficult to analyze and predict, since a process model must be realistic and should not neglect the effect of significant process variables.

The mathematical models and the computer programs capable of optimizing the shell drawing process for actual artillery shells and cartridge cases were developed earlier.(1) These mathematical models were based on the analysis of plastic deformations and included the effects of the various process variables (such as punch speed, billet temperature, and lubrication), the properties of shell, die, and punch materials, and the die configuration (both conical and streamline). These models were computerized so that they can be used to analyze the mechanics of the process and predict potential material failure (such as punch-through), and optimize the die configuration and process variables. These mathematical models were expanded to simulate shell drawing through multiple dies in tandem with a tapered punch, as shown in Figure 1. Graphical display capabilities were also included during computerization of the expanded math models.

Stress Analysis

The present model simulates the actual drawing process by dividing the punch movement into a finite number of discrete steps. The Sachs' method[2] of analysis was used to calculate stresses and drawing loads at each step. This analysis is valid for both conical and streamlined dies, since a complex die profile can be approximated by a series of straight lines.

Figure 2 shows a segment of the shell between the die and the punch, where the die is stationary and the punch is moving to the right. The operation consists of drawing a tube of outside radius R_o and inside radius R_i by a punch through a die to a tube of outside radius r_o and inside radius r_i. The details of the analysis of the stresses and the loads in this operation are given in Reference (3).

In calculating the stresses, the flow stress of each element is considered as a function of strain, strain rate, and temperature. The strain in an element is the cumulative strain, and strain rate is calculated from a velocity field developed during earlier studies.[1] The temperature of an element will depend upon the heat generated from plastic deformation, and friction at the tool-material interfaces, and the heat conduction to the colder dies and punch. Expressions for strain, strain rate and temperature of an element inside a die are also given in Reference (3).

Computer Model

Based on this stress analysis, a system of computer programs, named DRAWNG , was developed to simulate the drawing operation for artillery shell through multiple dies in tandem that employs a tapered punch. These computer programs are coded in FORTRAN IV and are applicable to both the cold and hot drawing of shells. A functional flow chart of DRAWNG is given in Figure 3. In its present form, DRAWNG is operational on a CDC system in interactive mode using a Tektronix graphics terminal. The die, billet and punch geometry are inputed to the program. This input can be read either through a data file prestored in the computer as a cataloged file or through the keyboard.

DRAWNG simulates the tandem drawing operation on a real-time basis, and the step-by-step results are displayed on the computer's graphic display terminal, as shown in Figure 4. On the top one-third of the screen, first the title is printed, and then the dies are drawn showing specified spacings between them, and the billet and punch are positioned for the beginning of simulation. Once the simulation begins, the step-by-step movement of the punch and the billet is shown on the top one-third of the screen. At the same time, the total ram load versus punch displacement and wall stress versus punch displacement are

424

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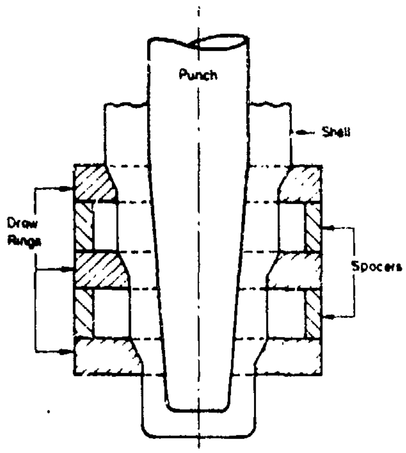


Figure 1. Tandem drawing with a tapered punch.

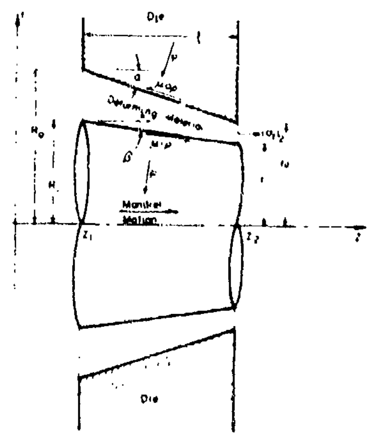


Figure 2. Drawing through conical die with a tapered punch.

In order to enhance the value of these mathematical models, confirmation tests under production or near-production conditions were conducted to substantiate them. The confirmation tests of the shell drawing operation at room temperature were conducted with 106.68mm (4.2-inch) M335 shell at Chamberlain Manufacturing Corporation's Waterloo, Iowa division under production and near-production conditions. The confirmation tests at hot forging temperatures were conducted with 155mm M107 shell at Chamberlain Manufacturing Corporation's Scranton, Pennsylvania division under production conditions. In both cases, tests were conducted using conventional conical and computer-designed streamlined dies. Finally, the evaluation of the mathematical models with the test results was conducted at Battelle.

MATHEMATICAL MODELING OF TANDEM DRAWING WITH A TAPERED PUNCH

The mathematical models developed earlier(1) were valid only for drawing through a single conical or streamlined die with a straight punch. Actual shell drawing operations, however, very often use more than one drawing die in tandem. Further, in these operations, the first portion of the punch is invariably tapered, as shown in Figure 1. Therefore, these existing mathematical models were modified to include drawing through tandem dies with a tapered punch.

425

shown on the left half and right half of the lower two-thirds of the screen, respectively. During the simulation, the computer programs calculate the correct flow stress in the deformation zone corresponding to local strain, strain rate, and temperature, and utilize appropriate equations for stresses, depending upon whether the element is free, or within a die, or in between two dies. In addition, the tensile strength of the product is plotted on the wall stress-versus displacement diagram to show whether punch-through is predicted at any stage of the drawing operation. At the end of simulation, the computer program provides messages which enable the user to enlarge any of the three diagrams on the screen.

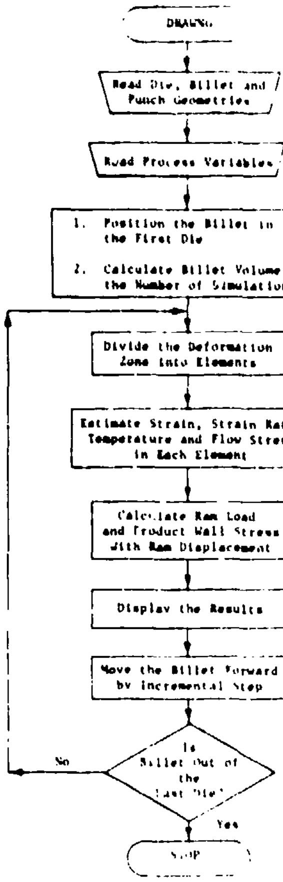


Figure 3. Functional flow chart of the computer program DRAWNG.

426

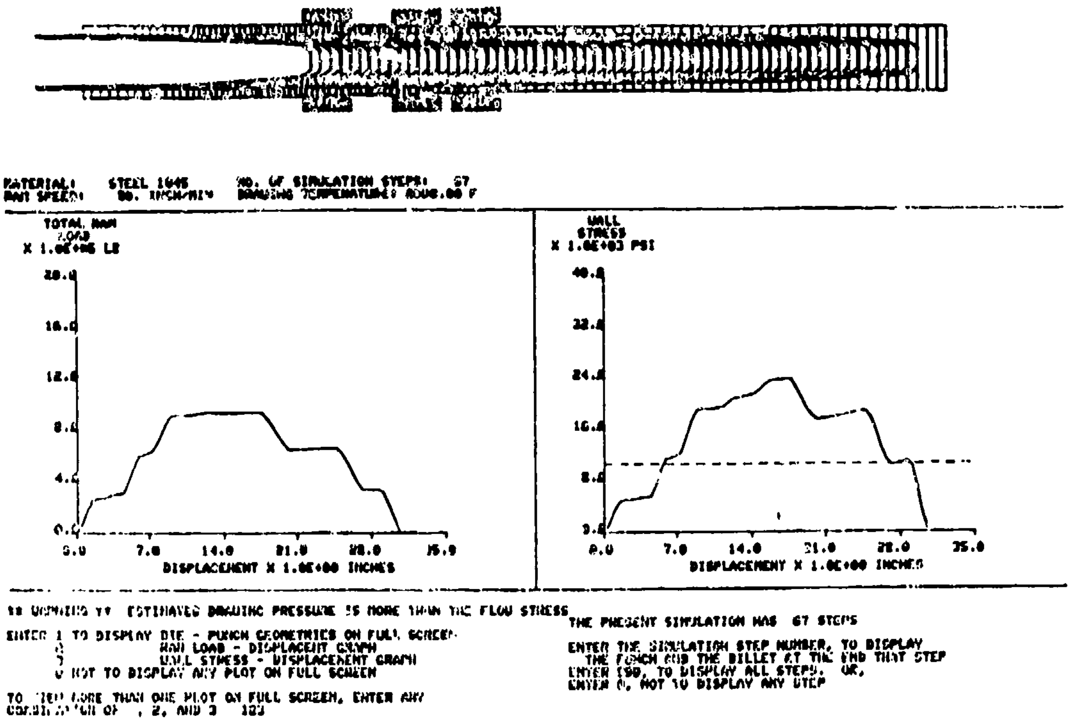


Figure 4. Simulation of tandem drawing as displayed on a CRT screen.

CONFIRMATION TESTING OF THE SHELL DRAWING OPERATION

Confirmation tests of the shell drawing operation were conducted under production or near-production conditions to evaluate the accuracy of the predictions. These tests were conducted at two different shell manufacturing plants. The cold drawing tests (at room temperature) were performed at Chamberlain Manufacturing Corporation's Waterloo, Iowa division under either production or near-production conditions. Hot-drawing tests (at hot-working temperatures) were conducted at Chamberlain Manufacturing Corporation's Scranton, Pennsylvania division under actual production conditions. In both cases, the tests were conducted with standard army shells which are under current production, and except for the drawing dies, the existing tooling (punch, die holder, etc.) were used. The tests were first conducted using conventional conical dies, and later they were repeated using the optimally designed streamlined dies with double-curvature profiles (designed based on prior mathematical modeling work on drawing of shell.[1]

427

Cold Drawing Tests

Confirmation tests of the cold drawing operation with conventional dies were conducted under an actual production environment at Chamberlain Corporation's Waterloo, Iowa division. For this purpose, the final double draw operation of 4.2 inch M335 shell (Figure 5) on a Bliss production hydraulic press was selected. The press is rated at 1.78 MN (200 tons), and has a 1020 mm (40-inch) stroke. The nominal ram speed is 68 mm/s (160 inch/min), and the ram diameter is 368.3 mm (14.5 inch).

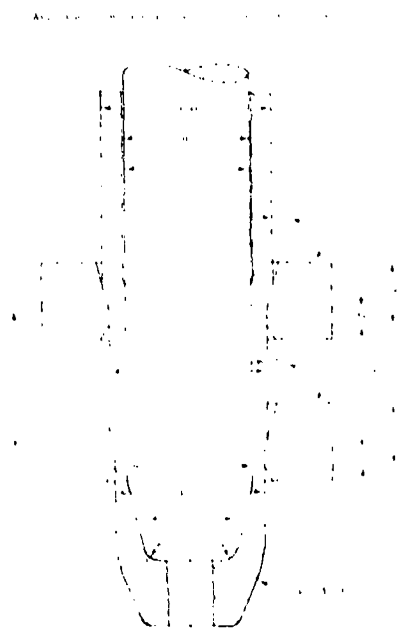
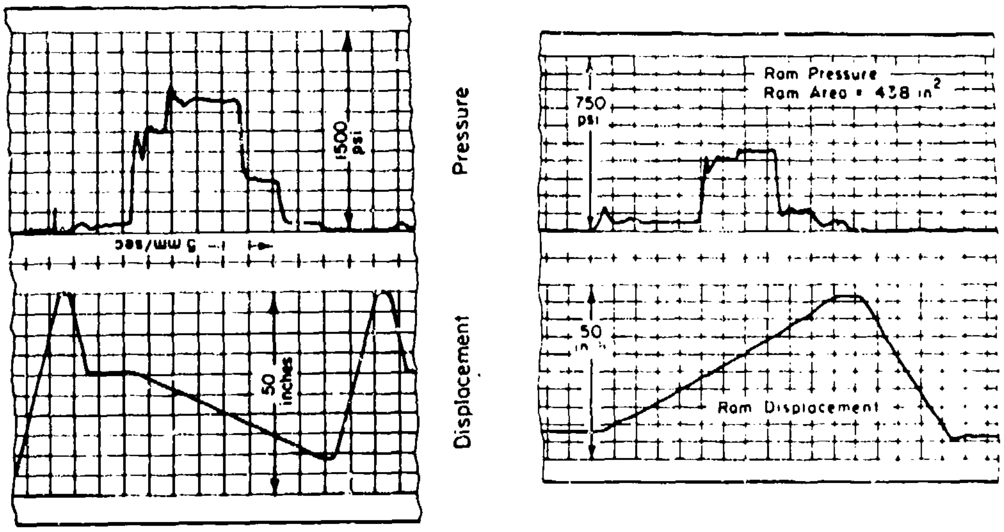


Figure 5. Schematic representation of final double draw of M335 shell.

Confirmation tests of the cold drawing operation with streamlined dies were conducted under near-production conditions in Chamberlain Corporation's Research and Development division at Waterloo, Iowa. These tests were performed on a Verson hydraulic press rated at 5.34 MN (600 tons) with a maximum ram displacement of 1.676 m (66 inch). This press has a nominal ram speed of 91.4 mm/s (216 inch/min) and ram diameter of 0.60 m (23-5/8 inch) ram area = 0.283 sq m (438 sq in.) . These presses were instrumented with pressure and displacement trans-

428

ducers, and the ram pressure and the ram displacement were recorded simultaneously on two separate channels of a two-channel brush recorder. At a selected interval, the ram pressure and ram displacement were recorded. The typical ram displacement plots for the conical and streamlined dies are given in Figure 6.



(a) Conical dies (b) Streamlined dies

Figure 6. Typical ram pressure and ram displacement recordings during cold drawing of M335 shell. (1 in. = 25.4 mm; 1 psi = 6.895 KN/m^2)

A few preforms and a few drawn shells were picked for detailed investigation. All the important dimensions, eccentricity and tensile properties were measured. The eccentricity of the drawn shells was almost always better than that of the preform. For the conical dies, the maximum, the minimum and the average peak loads were 0.804 MN (90.41 tons), 0.738 MN (82.98 tons), and 0.771 MN (86.69 tons), respectively. The measured loads for the deformation through streamlined dies were consistently lower. The maximum, the minimum and the average peak loads in this case were, 0.731 MN (82.19 tons), 0.673 MN (75.61 tons), and 0.687 MN (77.26 tons) respectively. Further, as seen in Figure 6(b), the breakthrough peak was typically absent here due to a more uniform deformation. The billet temperature after deformation was approximately 93.3°C (200°F) as compared to 104.4°C (220°F) in conventional drawing, also indicating a less severe deformation through streamlined dies.

429

Hot Drawing Tests

Confirmation tests of hot drawing operations with both conventional conical and streamlined dies were conducted for 155 mm M107 shell under actual production conditions at Chamberlain Corporation's Scranton, Pennsylvania division. These tests were conducted on the No. 1 Bliss press line which consists of a vertical hydraulic press. It has a load capacity of 3.56 MN (400 tons), a stroke of 3035 mm (120 inch), a nominal press speed of 0.466 m/s (1100 inch/minute), and a ram diameter of 511 mm (20.125 inch).

To measure ram load during the drawing operation, the hydraulic line of the press was tapped with a pressure transducer, and its conditioned output was connected to one of the two channels of a strip recorder. The second channel of the recorder was connected to the output from a displacement transducer to measure the ram displacement. The temperatures of the incoming billet (after cabbaging and piercing) and of the product were measured with an infrared digital pyrometer. The temperatures of the dies were measured periodically with a contact pyrometer.

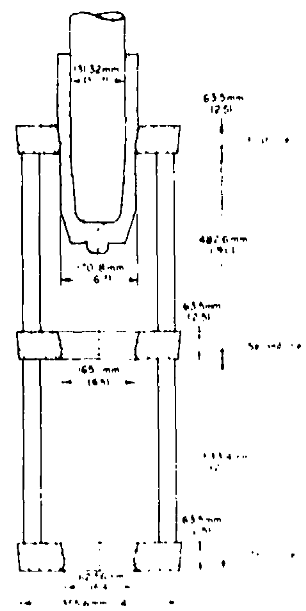


Figure 7. Schematic representation of hot drawing of 155 mm M107 shell.

430

A schematic representation of the hot drawing operation is shown in Figure 7. As in the case of cold drawing of shells, the general practice in industry for hot drawing of shells is to use dies with a conical entrance. The general configuration of the three dies used for hot drawing of 155 mm M107 shell under actual production has two entrance angles. Incoming material first touches the dies on a 10-degree segment at the die entrance. The 12-degree segment on the die entrance is primarily for easy centering of the workpiece in the top die. Prior to the beginning of the first shift on the day of the testing, the dies were replaced with a new set and were flame heated as usual and the press was instrumented to record ram pressure and ram displacement on a two-channel strip recorder. The load, displacement and temperature measurements were made every 15 minutes. A typical ram pressure and ram displacement recording is shown in Figure 8.

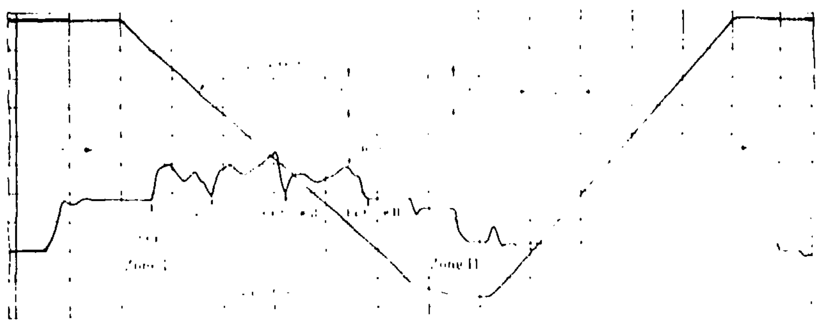


Figure 8. Typical ram pressure and ram displacement recording during hot drawing of M107 shell through conventional conical dies. (1 in.= 25.4 mm; 1 psi = 6.895 KN/m^2)

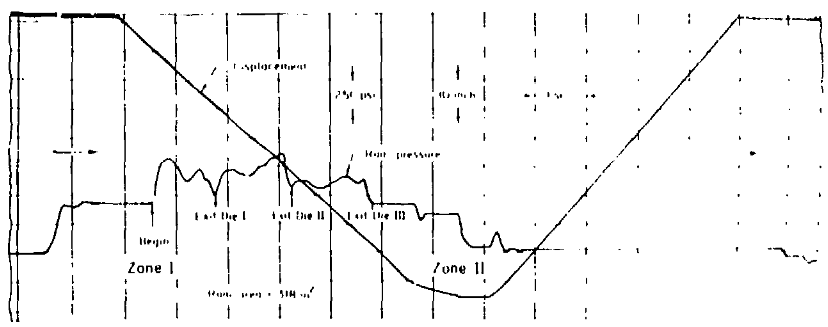


Figure 9. Typical ram pressure and ram displacement recording during hot drawing of M107 shell through streamlined dies. (1 in. = 25.4 mm; 1 psi = 6.895 KN/m^2)

431

In the present mathematical modeling studies, the interface friction shear stress is defined by

$$\tau = \frac{m}{\sqrt{3}} \bar{\sigma} = f \bar{\sigma} \qquad (2)$$

where $f = m/\sqrt{3}$ is the friction factor and its value could be between 0 and 0.577.

The interface friction shear factor in cold drawing was characterized using the well known ring test.(4) For phosphate and soap lubrication used in cold drawing, the friction factor m=0.06 (f=0.35) was used.

The load-displacement curves, predicted by the computer program DRAWNG for both conical and streamlined die arrangements were evaluated. For this purpose three cases were selected corresponding to the maximum, minimum, and average peak ram load recorded during each of the tests. For each of these selected cases, the theoretical load-displacement curve was generated using actual dimensions of the preform and the product. Theoretically predicted and experimentally measured load-displacement curves (corresponding to maximum recorded peak load), for drawing through two conical dies in tandem, are compared in Figure 10. Overall agreement between predicted and measured curves is very good. The predicted peak loads are somewhat higher because the upper bound approach was used in the analysis. The slight mismatch on the displacement axis is primarily due to initial positioning of the preform in the second die, since its forward end is contoured (see Figure 5) and does not match the die contour. Similar agreement were found for curves corresponding to the minimum and average peak loads.

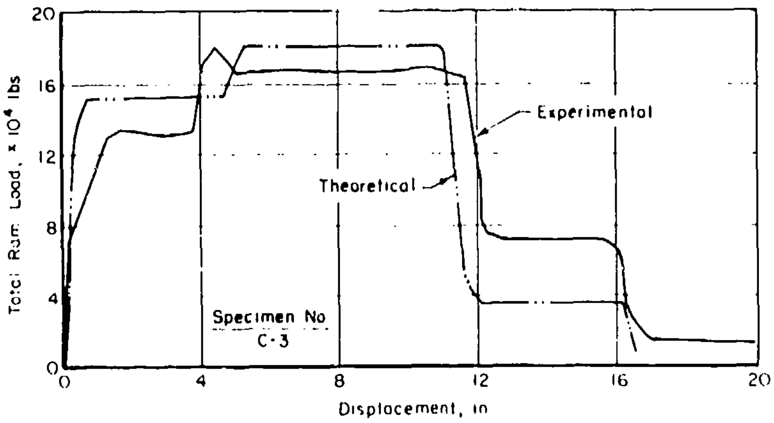


Figure 10. Theoretical and experimental load-displacement curves for cold drawing of M335 shell through two conical dies in tandem. (1 in. = 25.4 mm; 1 lb. = 4.448 N)

432

Following the tests with conventional conical dies, hot drawing tests with streamlined dies were conducted during a production run on the next day. Again, the dies were replaced during the night shift prior to the day of tests. As in the case of tests with conventional conical dies, the press was instrumented to record ram pressure and displacement, and temperature. Ram pressure and ram displacement were recorded every 15 minutes. The production with the streamlined dies was monitored for about 6 hours, and the dies consistently produced good parts. A typical ram pressure and ram displacement recording during these tests is shown in Figure 9. Although the ram pressure curve in Figure 9 does not look much different than that in Figure 8, on the overall, the operation with streamlined dies appeared quieter and smoother compared to the operation with the conical dies. This set of dies produced a total of 15,836 parts before they needed replacement. Engineers at Chamberlain stated that this die life was short, but it may not be totally attributable to the die design.

EVALUATION OF MATHEMATICAL MODELS

The predictions from the computer program DRAWING were evaluated with respect to the results from cold and hot drawing confirmation tests. For this purpose, it became necessary to characterize the flow stress and the interface friction factor under both cold and hot working conditions. The flow stress data were obtained from tension tests, and the friction factor was determined by conducting ring tests.[4]

Cold Drawing Operations

Interface friction and flow stress are two basic inputs required in the program DRAWNG. Since deformation in shell drawing occurs primarily due to tensile stress, the material flow stress should be determined under tensile loading. Therefore, a randomly selected preform was cut and tension specimens of 6.35-mm (0.25-inch) gage diameter were machined. These specimens were tested in an Instron testing machine at a crosshead speed of 0.04 mm/s (0.100 inch/min). Load versus displacement was recorded at a constant chart speed, and later it was reduced into true stress ($\bar{\sigma}$) versus true strain ($\bar{\varepsilon}$) curve. In order to use this information in the computer program DRAWNG, a least square mean fit to the experimental points was developed as given below:

$$\bar{\sigma} = 772 \ (\bar{\varepsilon})^{0.1822} \ (MN/m^2). \qquad (1)$$

433

Experimental load-displacement curves, corresponding to the maximum, peak load for cold drawing of M335 shell through two streamlined dies (designed by the computer program CDVEL[1], are compared with the theoretically predicted load-displacement curves in Figure 11. The mathematical model in these cases predicts higher peak loads compared to measured peak loads. However, overall agreement between predictions and measurements is good for all engineering purposes. In addition, these dies proved to produce good parts, required approximately 13 percent less force and energy, and the breakthrough peak was typically absent compared to the conical dies in a similar tooling arrangement.

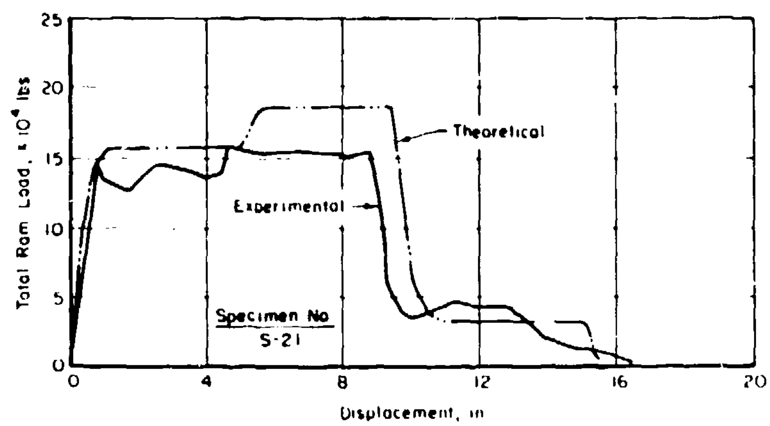


Figure 11. Theoretical and experimental load-displacement curves for cold drawing of M335 shell through two streamlined dies in tandem. (1 in. = 25.4 mm; 1 lb. = 4.448 N)

Hot Drawing Operations

The flow stress for AISI 1045 steel at hot working temperatures and strain rates was taken from Reference 4. An average value of the friction factor f = 0.35 was selected based on an independent ring compression study for hot forging of steels.

To evaluate the load-displacement curves predicted by the computer program DRAWNG for hot drawing of M107 shell through conical and streamlined dies, three different cases for each type of dies were selected. Hot dimension of the preform was calculated from cold dimensions of the preform measured during trials. However, the effective length of the preform varied considersbly, from 342.9 mm (13.5 inch) to 368.3 mm (14.5 inch). Punch dimensions were taken from the shape of the base of the finished product. Tool assembly, as shown in Figure 7,

434

was considered.

Length of the preform has considerable effect on overall shape of the load-displacement diagram. If the preform length is on the shorter side, the load drops nearly to zero as the product exits the first die and the peak near the exit from the second die is small. This behavior is shown in the theoretical curve in Figure 12, where the preform length was taken as 342.9 mm (13.5 inch). On the other hand, if the length of the preform is on the higher side, the product is picked up by the second die as soon as it exits from the first die, and the peak near the exit from the second die is relatively high, since the shell is in the second and the third die at the same time. This behavior is shown in the theoretical curve in Figure 13, where the effective preform length is taken as 368.3 mm (14.5 inch). Therefore, for evaluation purposes, an average preform length (effective) of 355.6 mm (14.00 inch) was taken. With this length of the preform, the trend observed in experiments were also reproduced by computer predictions, as shown in Figure 14. Overall agreement is good; peaks and valleys in the theoretical curves are somewhat sharper than measured. This is basically due to the simplified heat generation and heat transfer analysis used in the present model. However, the peak loads correlate well with the experimental measurements, except under the third die. This is, again, believed to be due to simple heat transfer analysis to a certain extent and due to the complex preform shape used in production compared to one assumed in the present analysis. In general, agreement between the theory and experiment appears good.

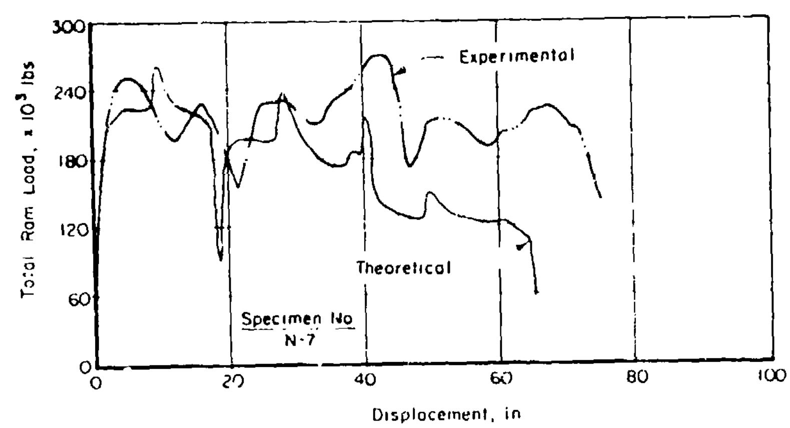


Figure 12. Theoretical and experimental load-displacement curves for cold hot drawing of M107 shell through conical dies for preform length = 342.9 mm (13.5 inch).

435

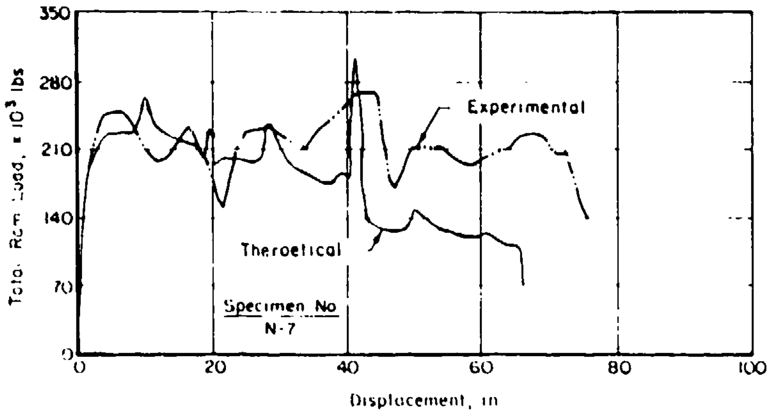


Figure 13. Theoretical and experimental load-displacement curves for hot drawing of M107 shell through conical dies for preform length = 368.3 mm (14.5 inch).

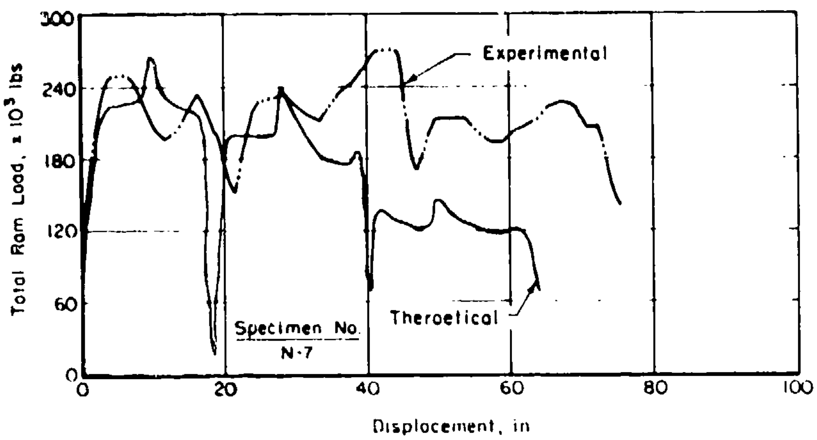


Figure 14. Theoretical and experimental load-displacement curves for hot drawing of M107 shell through conical dies for preform length = 355.6 mm (14.0 inch).

(436)

Similar comparisons of load displacement curves for hot drawing through streamlined dies were made. Considering the fact that preform dimensions and friction at the interfaces (due to different amount of scale) in hot drawing vary from piece to piece, correlation between the theoretically predicted and experimentally measured load displacement curves is good. Again, predicted loads through the third die were lower than measured values. This discrepancy is partially due to the difference between theoretical and actual preform shape, as discussed earlier. However, this error is not considered of any significance since process design and equipment selection in reality is primarily based on the peak loads in the process.

CONCLUSIONS

Mathematical models for optimization of the shell drawing process were expanded to consider drawing through multiple dies in tandem and tapered punch and coded in computer program DRAWNG. DRAWNG is capable of simulating the shell drawing process, both hot and cold, and generate the ram load and the product wall stress versus ram displacement diagrams during simulation on a Cathode Ray tube (CRT). Predictions from these models were evaluated with respect to hot and cold drawing confirmation testings conducted under actual or near production conditions. In addition, these tests included an evaluation of the streamlined dies, designed by the computer program CDVEL developed earlier.[1]

Conclusions of the present study are:

(1) The system of computer programs DRAWNG is capable of simulating both the cold and hot shell drawing using single or multiple dies (both conical and streamlined) in tandem with a tapered punch.

(2) Comparisons between theoretically predicted and experimentally measured ram load versus ram displacement curves indicate that computer programs DRAWNG are capable of predicting load-displacement curves, both under hot and cold drawing conditions.

(3) Success of all experiments was predicted by the computer program since good parts were produced in the cold and hot drawing operations and no material failure had occurred.

437

(4) Streamlined dies designed by using the computer program CDVEL produced good parts, both dimensionally and property-wise, under actual production environment in the manufacturing of M335 and M107 shells.

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(438)